A Physics-Based Terrain Model for Off-Road Vehicle Simulations

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14. ABSTRACT
-Motivation & goals of project -High level model Framework -Detailed Calculation Flowchart --Concentrates on advancing simulation by one time-step -Examples of terrain response to various applied loading conditions -Addressing performance issues through parallel computing -Conclusion

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Overview

- Motivation & goals of project
- High level model Framework
- Detailed Calculation Flowchart
  - Concentrates on advancing simulation by one time-step
- Examples of terrain response to various applied loading conditions
- Addressing performance issues through parallel computing
- Conclusion

Motivation

- Existing vehicle dynamics models incorporate deformable terrain in two general ways:
  1. Empirical methods
     - WES numerics, Bekker vertical pressure/sinkage
  2. Boundary Value Problem
     - Finite Element Analysis (FEA)
     - Particle/Discrete Element methods (DEM)

- Empirical methods are not suitable for general purpose vehicle mobility, energy/power, durability/reliability analyses

- FEA or DEM are accurate, but are computationally expensive and cannot achieve real-time performance

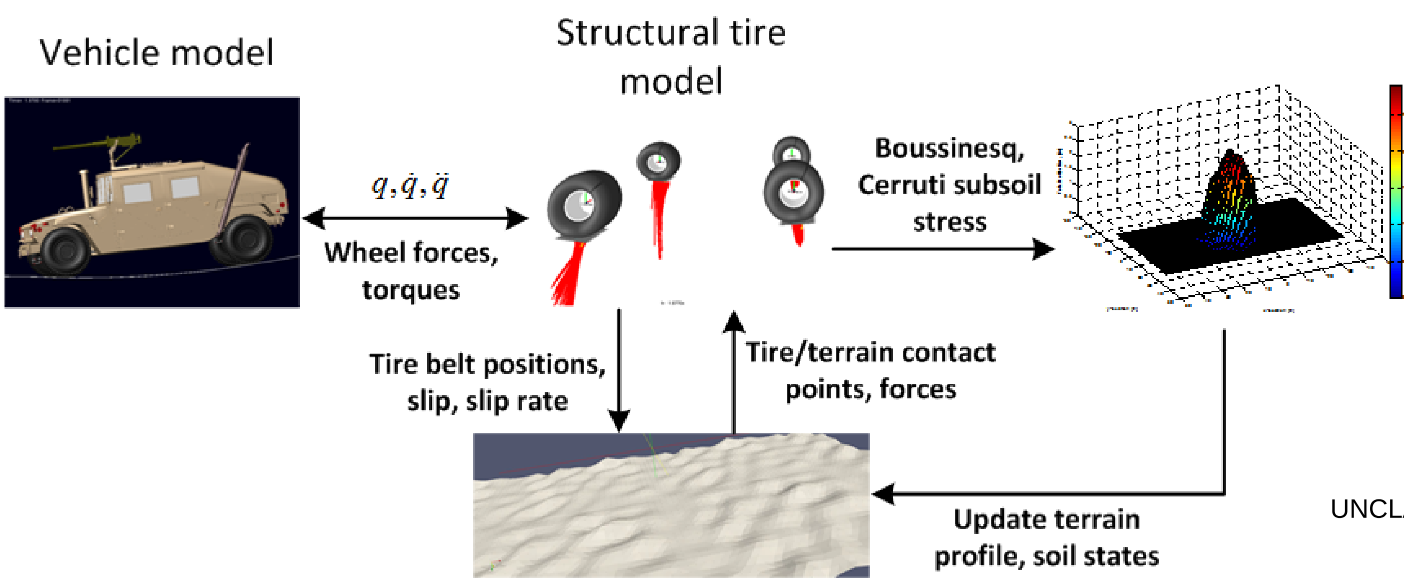
- Requires a lower-order, physics-based tire/terrain model that can interface to existing multibody-dynamic vehicle models

Overall Goals of Project

- Link existing vehicle models to physics-based deformable terrain interaction model
  - Soil Mechanics models developed by UT (Ayers, Bozdech)
  - Soil models and terrain database implemented by UW (Madsen, Seidl)
- Tire/terrain interaction model should run at real-time speed
  - Enables operator-in-the-loop simulations
  - Requires multi-core CPU and GPU parallel computing acceleration
- Develop universal vehicle/terrain model for deformable terrain that is capable of mobility, power/energy and reliability analysis

High level Framework

- Interface begins at the wheel spindle
- Can use any tire model that satisfies:
  1. Standard Tire Interface
  2. Accepts a discrete contact patch geometry to find force vectors at the interface
- Tire/Terrain interface forces assumed as a combination of radial, slip and bulldozing effects
- Interface forces applied to terrain to find subsoil stress beneath tire
- Soil deforms vertically according to visco-elastic-plastic compressibility relationship, in conjunction with loading history
  - Includes compression/rebound, repeated loading effects



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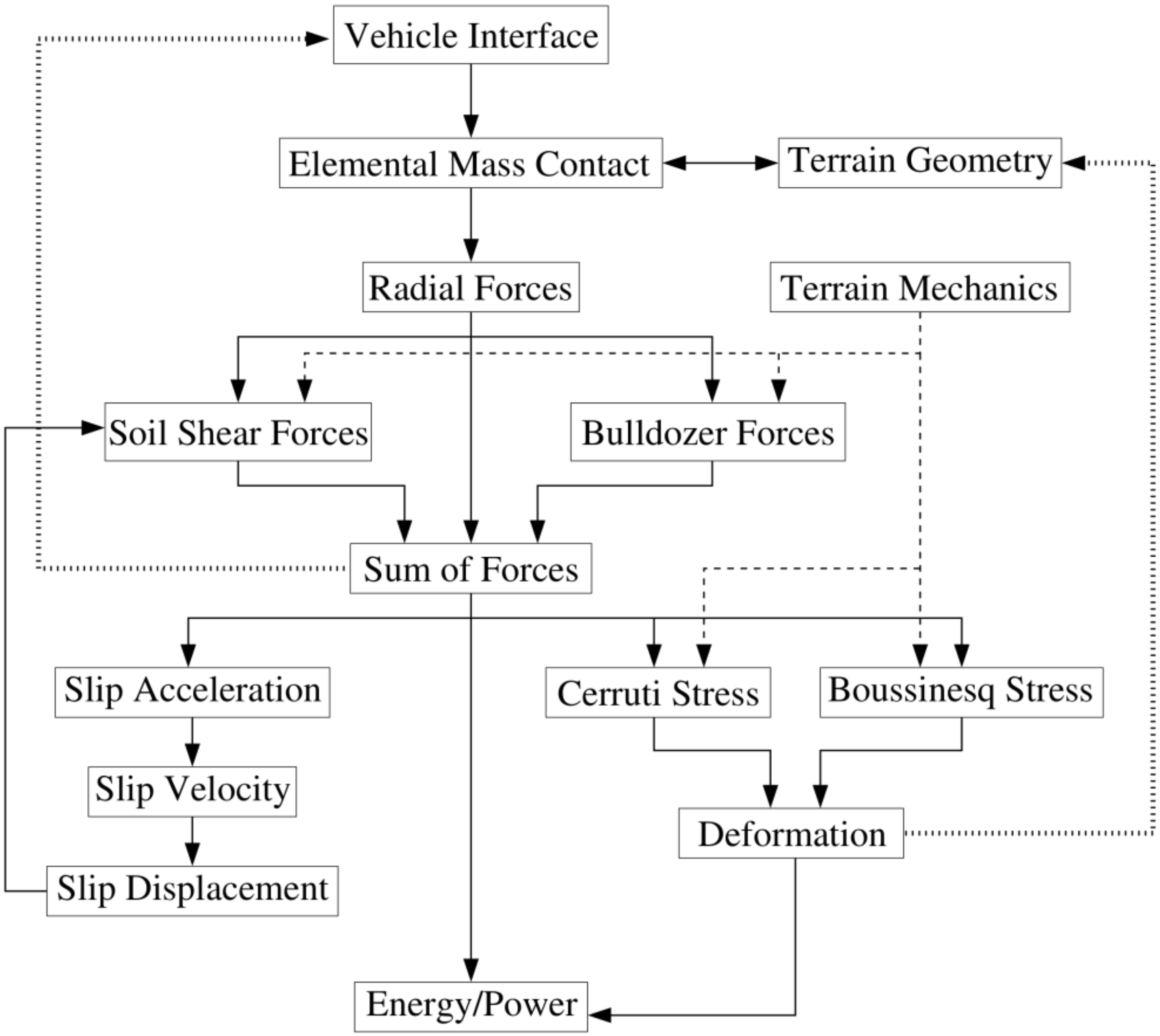
Simulation, taking one time-step…

- Modeling assumptions
  - Tire and terrain dynamics solved in a staggered fashion
  - No tire dynamics considered here (i.e., rigid wheel)
    - Slip computation is more involved with a deformable wheel

- Summary of major required computations
  - Identify contact between tire and terrain
  - Calculate contact patch force/pressure
    - Normal forces as a function of tire-terrain interpenetration
    - Tangent forces developed from slip & bulldozing effects
  - Contact patch forces used to approximate stress field in subsoil
    - Modified Boussinesq, Cerruti theory
    - Assumes linear superposition of subsoil stresses
  - Terrain model calculates:
    - Soil element stress-displacement effects
    - Power and energy to perform soil deformation
    - Updates soil states and terrain surface profile change

Detailed Calculation Flow



Quasi-static Contact Patch Model

- Need to have a force model at the tire tread/soil interface
- Tread deformations are fast & small when compared to carcass deformations (Svendenius, 2006)
  - Tire carcass model → Dynamic
  - Contact patch model → Static

- Contact patch pressure calculated at each discretized tire node once per time step
- Combines of normal, tractive and bulldozing effects

Contact Patch Model: Normal Forces

- Assume tire normal forces are approx. radial and a function of interpenetration between tire belt mass nodes and terrain geometry, δ_n^i
  - Using a penalty-based repulsion force
  - Able to use static vertical load tests to approximate radial stiffness per unit area, k_n

$$\sigma_n^i = \delta_n^i k_n \vec{n}^i$$

  - where

$$\vec{n}^i = (P_a^i - P_0^i)$$

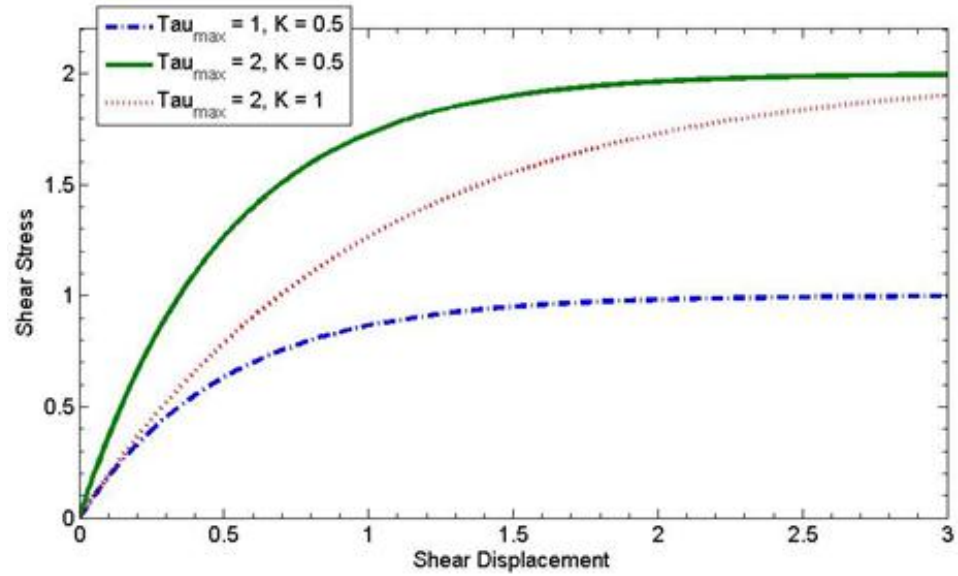
Contact Patch Model : Tire Slip and Bulldozing Forces

- Tire slip at the tire-terrain interface generates tangential forces
  - Responsible for tractive and turning forces
  - Janosi and Hanamoto model (1961)

$$\tau = \tau_{\max}(1 - e^{-j/K})$$

$$\tau = (c + p\tan\varphi)(1 - e^{-j/K})$$

  - Based on total slip displacement, soil shear attributes

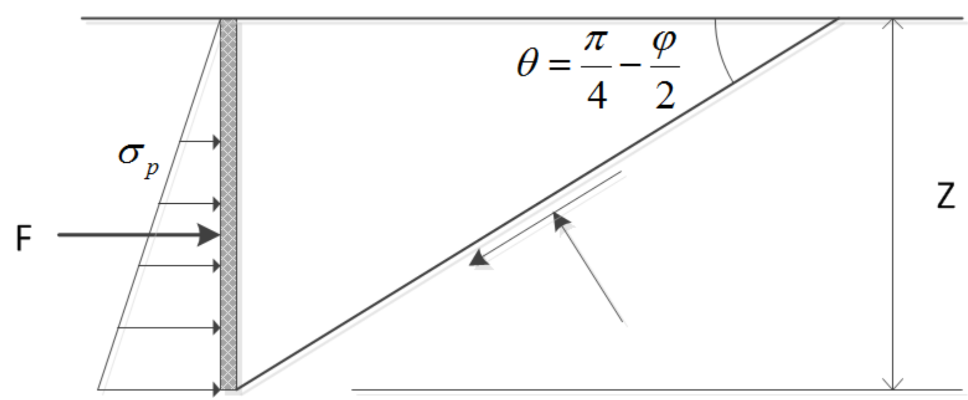


- Bulldozing effects add additional forces
  - Increases turning (lateral) forces
  - Reduces tractive (longitudinal) forces
  - Passive Lateral Earth Pressure Theory (Wong, 2001)

$$F = b(\tfrac{1}{2}\gamma Z^2 N_\phi + 2cZ\sqrt{N_\phi})$$

$$N_\phi = \tan^2(45 + \phi/2)$$

  - Force a function of: tire sinkage, soil friction angle and soil bulk density



Terrain (Compaction) Model: High Level Perspective

- Sum of normal, slip and bulldozing forces acting on tire are applied to the terrain surface
- Soil volume discretized into rectangular grid
- Only consider vertical stress-strain in soil (“Compaction”)

- Subsoil stress distribution calculated via. modified Boussinesq & Cerruti Equations

- Vertical subsoil pressure at the top of each element can cause bulk density change according to Visco-Elastic-Plastic soil model

- Soil element deformation and current soil state allow calculation of energy, power. **Discretized soil grid allows for power & energy distribution calculation**

Subsoil stress distribution

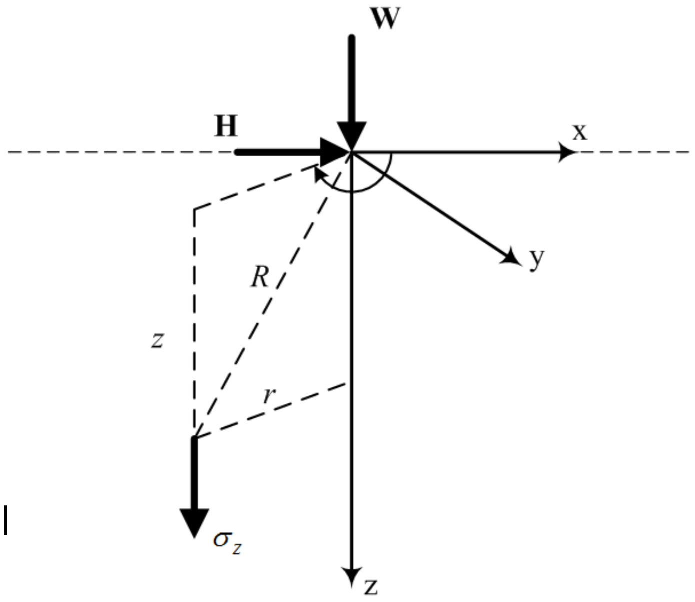
- Empirical in nature
- Vertical force results in stress via. Boussinesq according to Frolich (Ayers, 1991)

$$\sigma_z = \frac{\nu W z^{\nu}}{2\pi(r^2 + z^2)^{(\nu/2+1)}}$$

- Horizontal force also results in stress via. Cerruti (Feda, 1978)

$$\sigma_z = \frac{3}{2\pi}\frac{r(\cos\Theta)}{[1+(r/z)^2]^{5/2}}\frac{H}{z^3}$$

- Only calculate subsoil stress distrubtion di
underneath contact patch
- Limit the maximum subsoil stress to the contact patch pressure at the surface



Visco-Elastic-Plastic soil model

- Vertical subsoil stress known at discrete points
- Theoretical bulk density for given M.C., stress (Larson et al., 1980):

$$\rho = \left[\rho_k + S_T\left(S_1 - S_k\right)\right] + C\log\left(\sigma_a / \sigma_k\right)$$

- Include time-constant effects to bulk density

$$\left(1 - e^{t/\tau}\right)$$

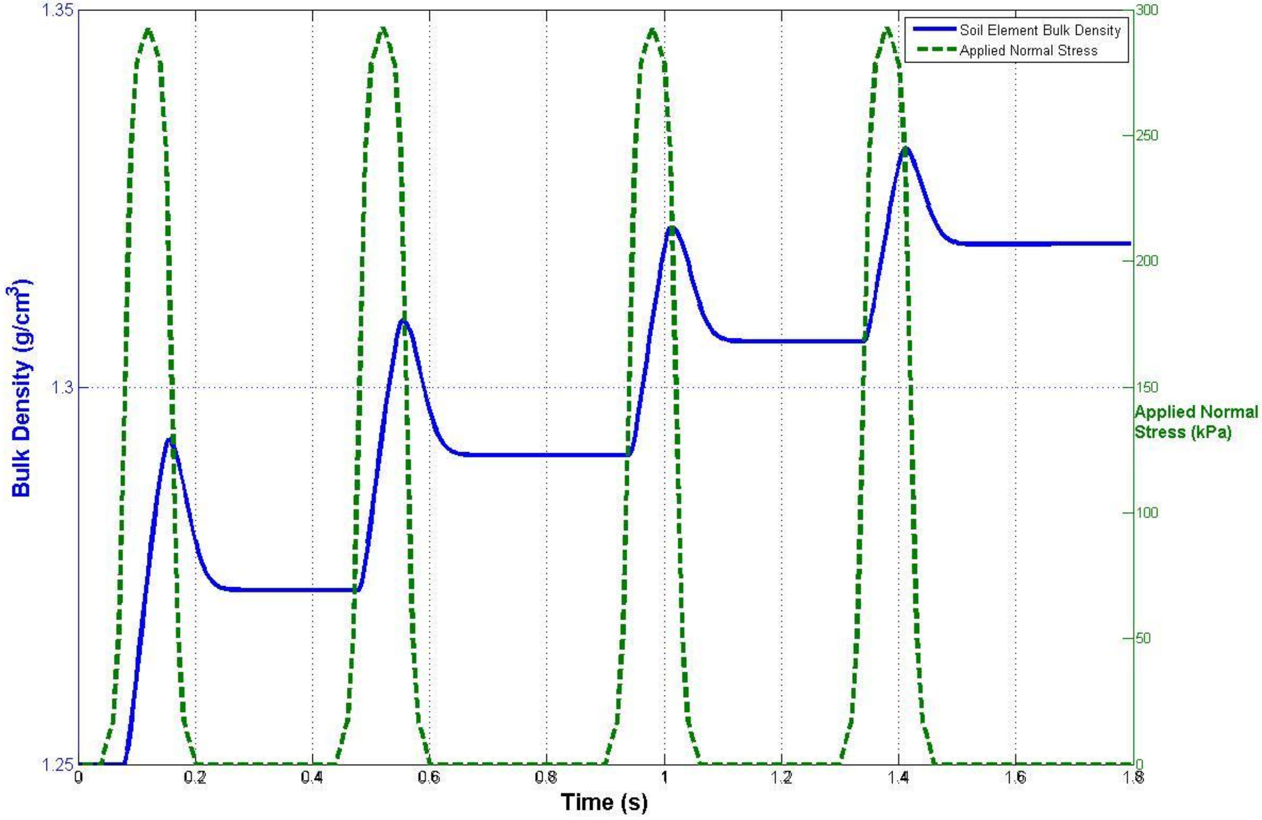
- Sinkage simply a function of initial, current bulk densities

$$z = \left(1 - \left(\rho_0 / \rho_1\right)\right)$$

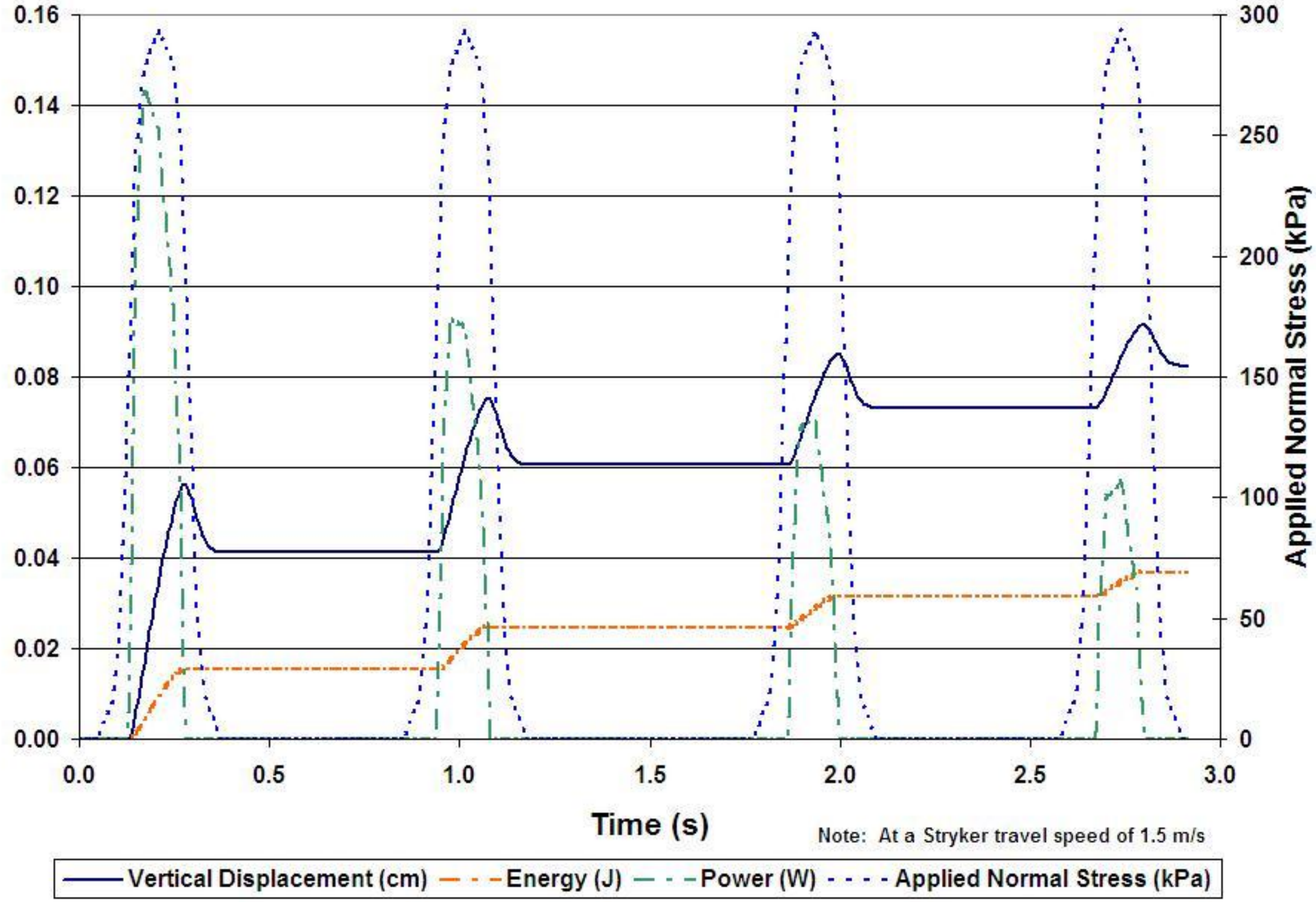
- Power, Energy simply calculated as

$$E = F \cdot \Delta z = (\sigma \cdot A) \cdot \Delta z \qquad P = E / \Delta t$$

Soil Response to Surface Loads

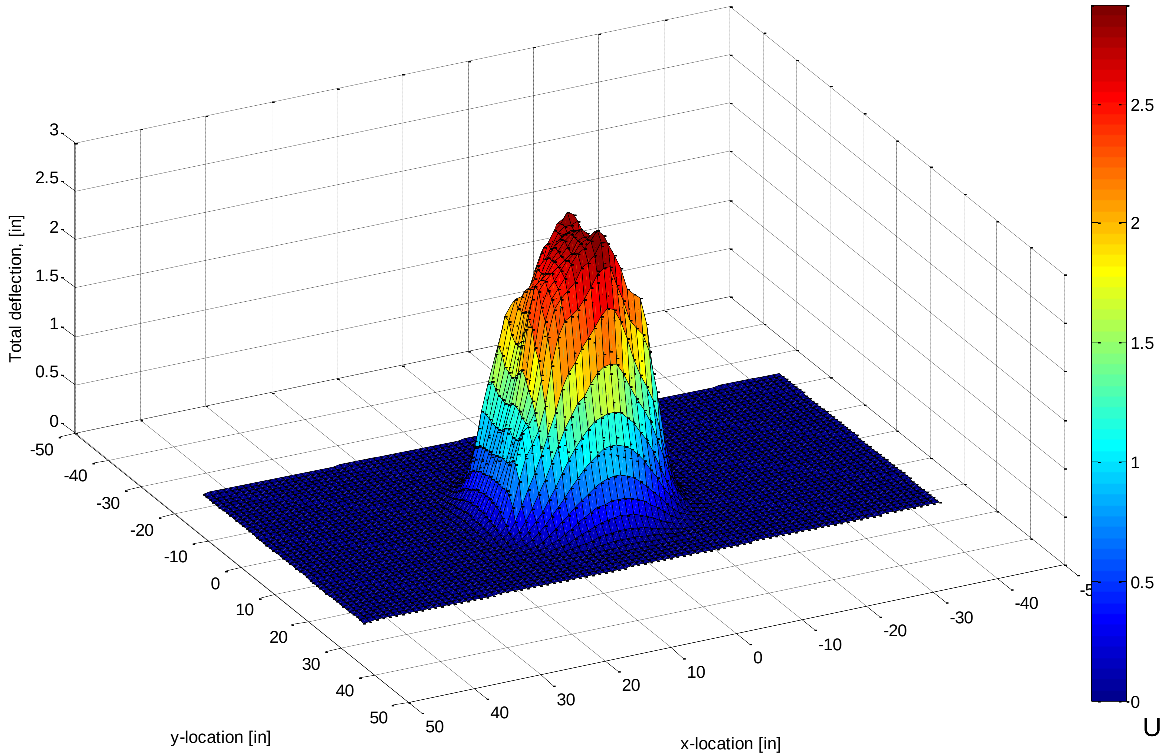


Soil Response to Surface Loads



Example Simulation Results, Vertical Deflection

- Database tracks soil state at many points, which allows for the calculation of: overall soil deflection, energy and power required
  - Ex) Using a rigid tire
    - Vertical deflection of tire: 5” compression, followed by 5” rebound



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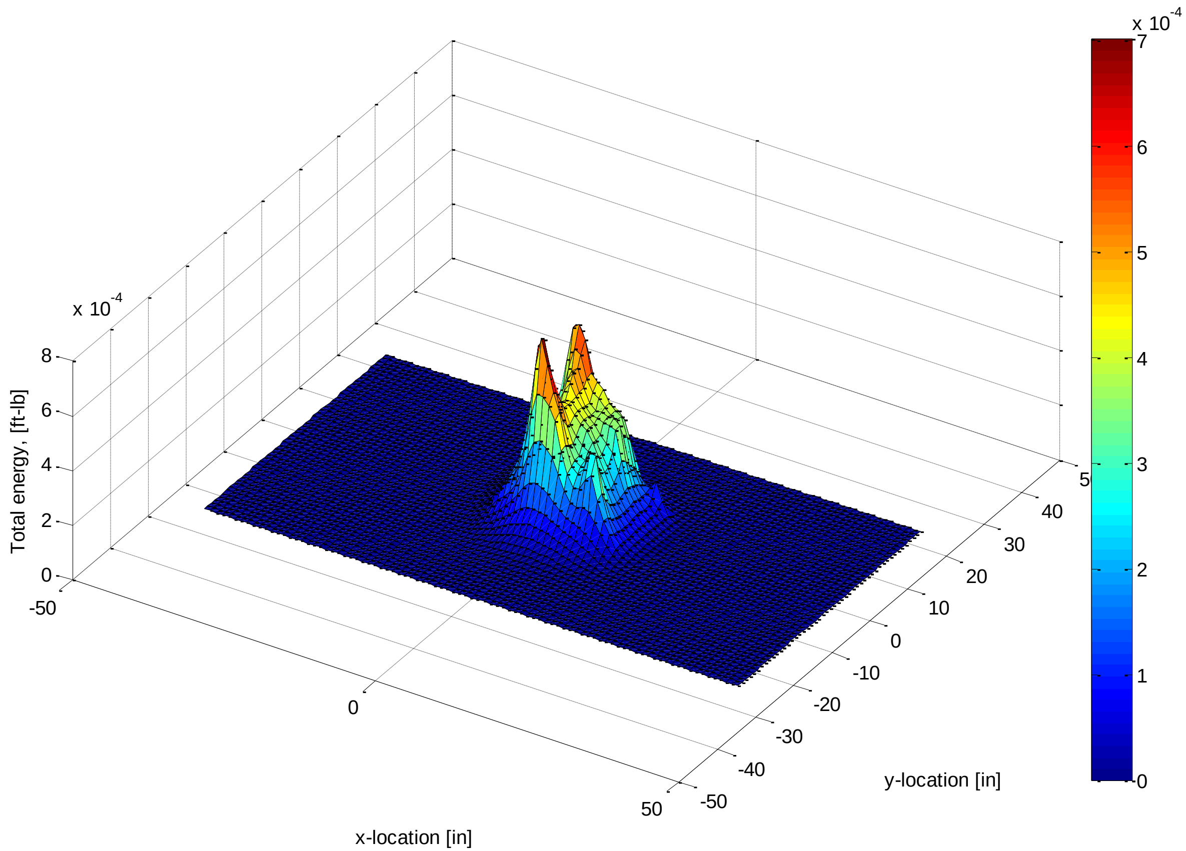
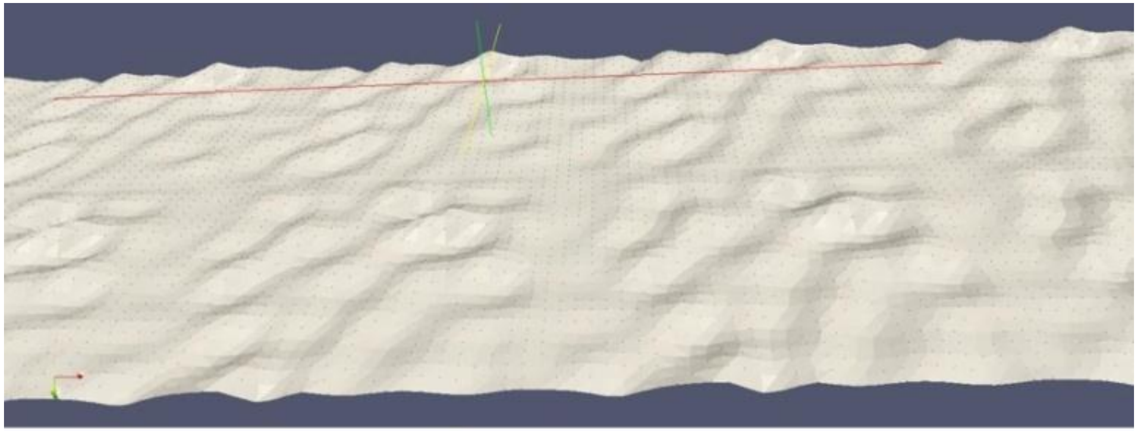
Example Simulation Results, Energy

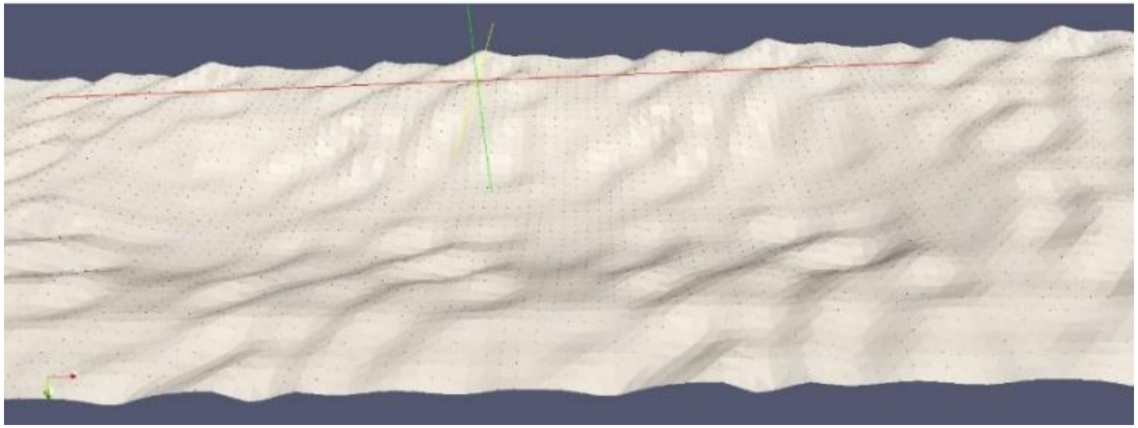
- Can calculate the energy required to deform the terrain at each timestep
- Can calculate the overall energy dissipation from plastic soil deformation



Example Simulation Results, Forward rolling

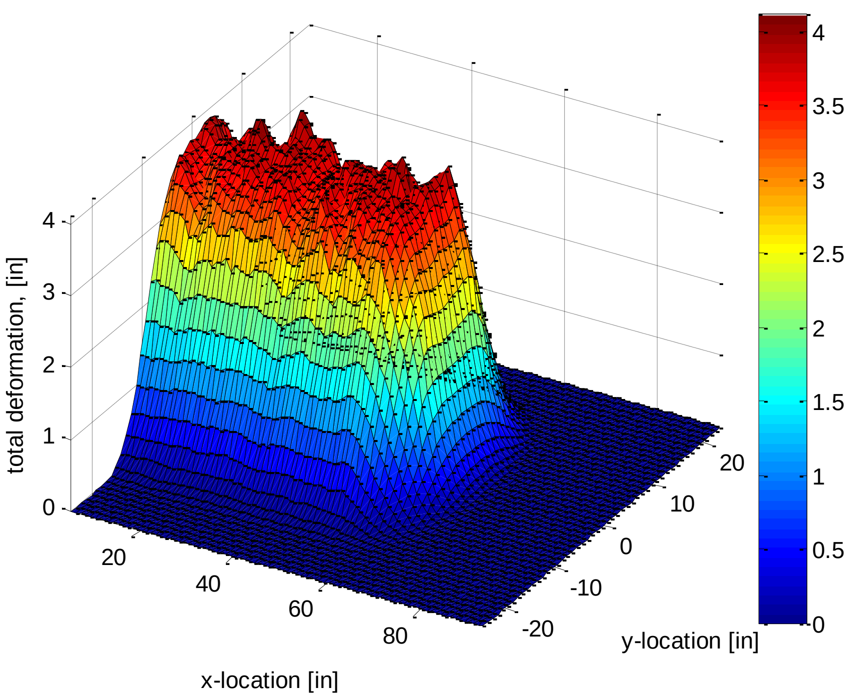
- Vertical deflection of tire: 5” compression
- Followed by traveling at a steady state velocity of 1.5 MPH.
  - An applied rotational displacement of the tire ensures that the tire is operating at minimal slip

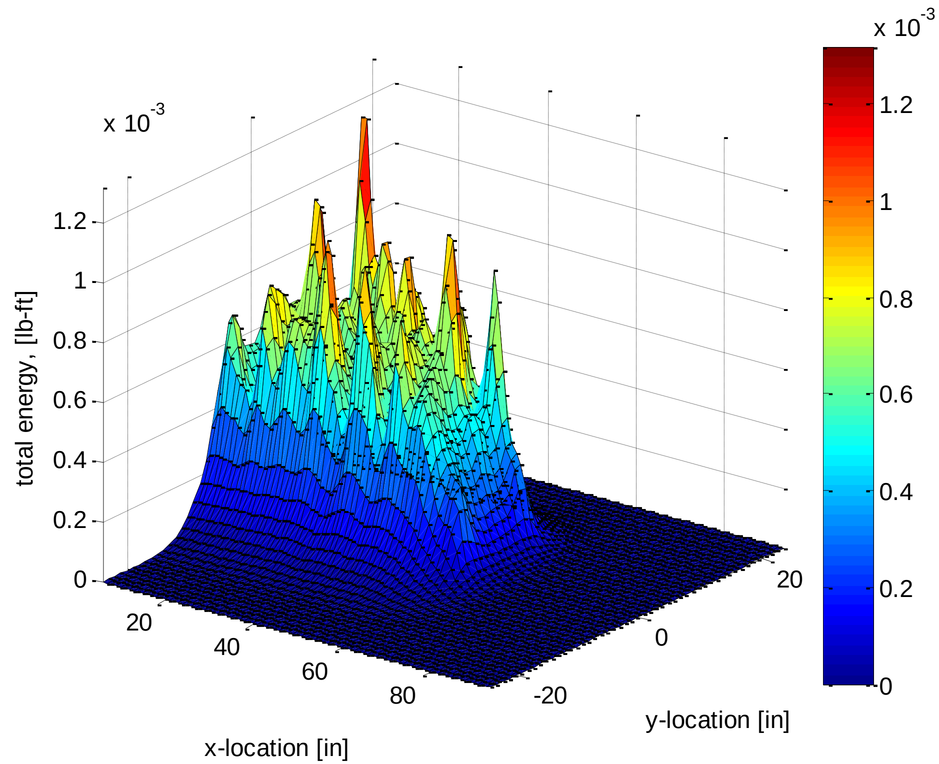




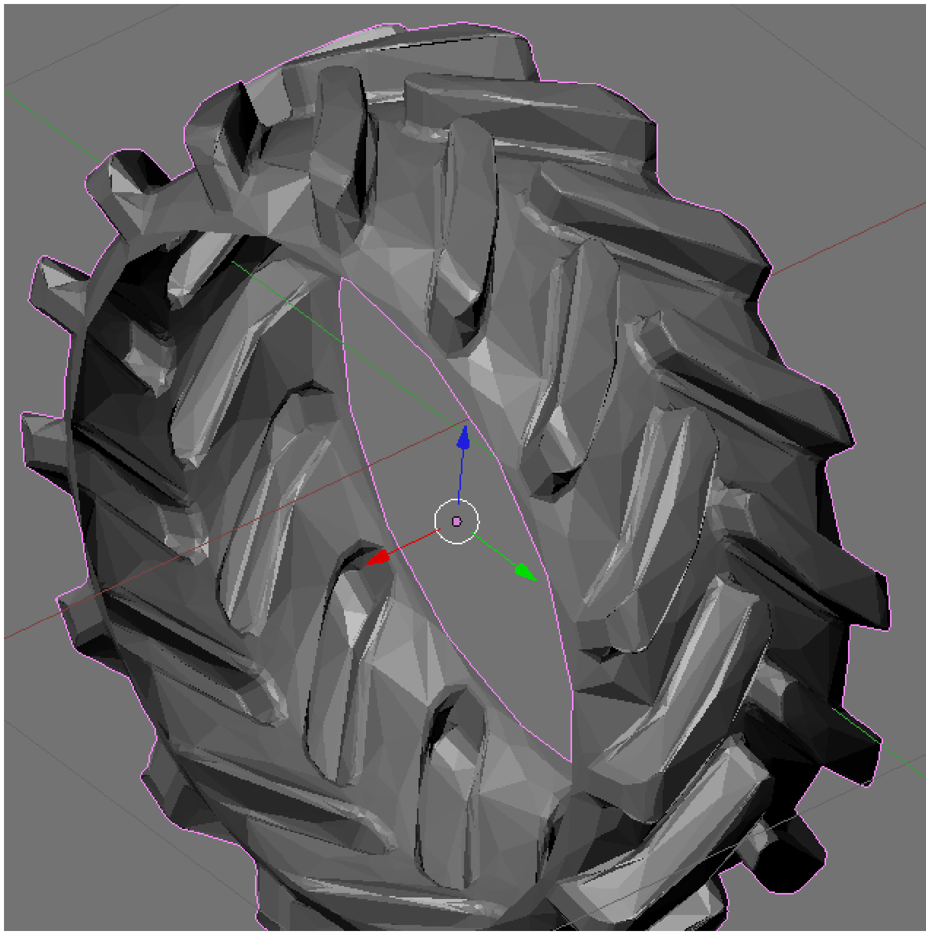
Example Simulation Results, Forward rolling

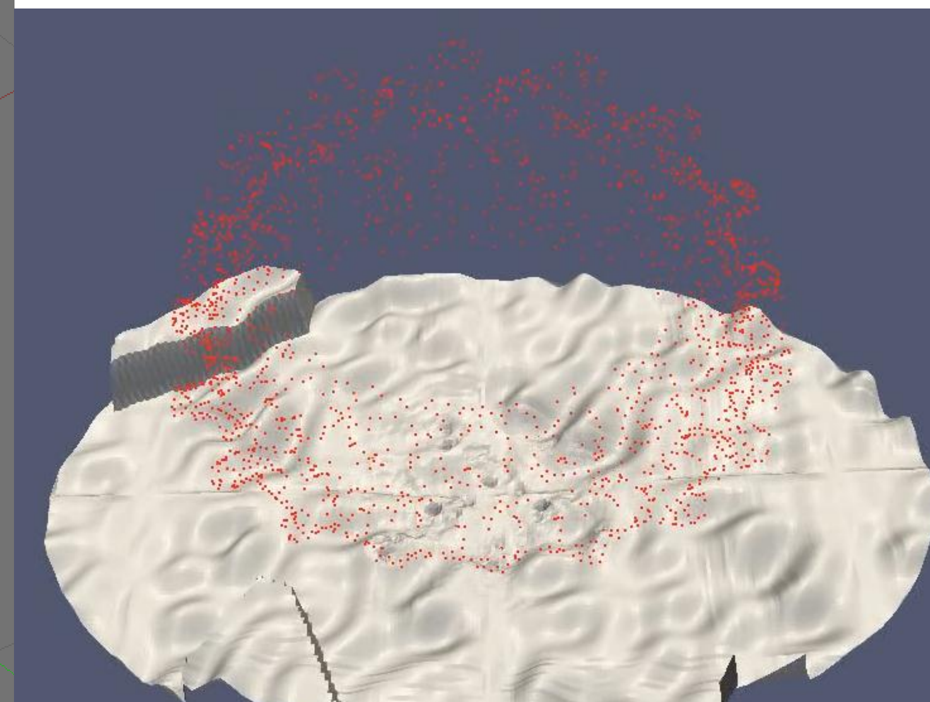
- Total soil displacement and deformation energy (right)



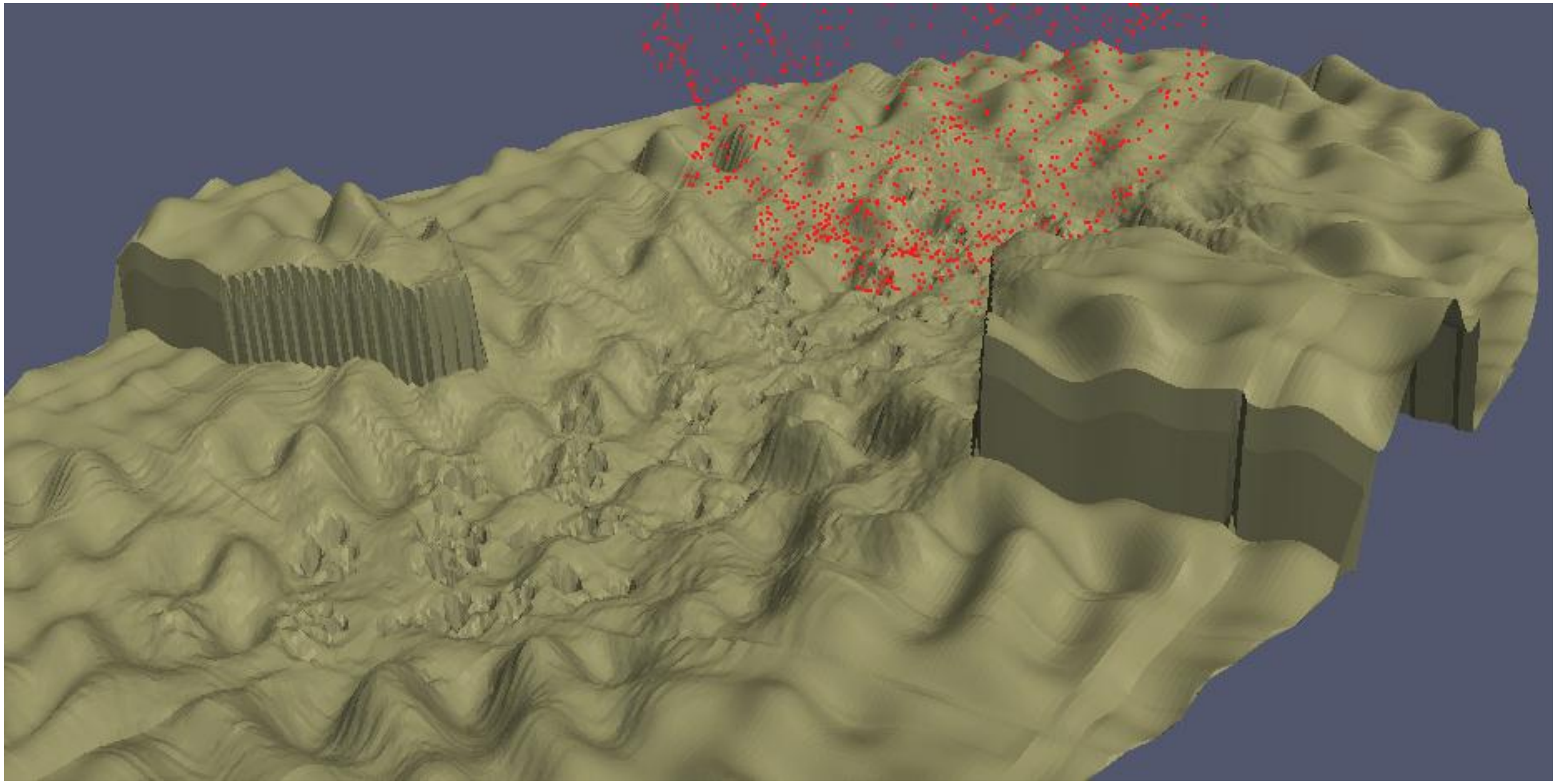


Terrain Deformation Rigid Tire with Lugs





Terrain Deformation Rigid Tire with Lugs



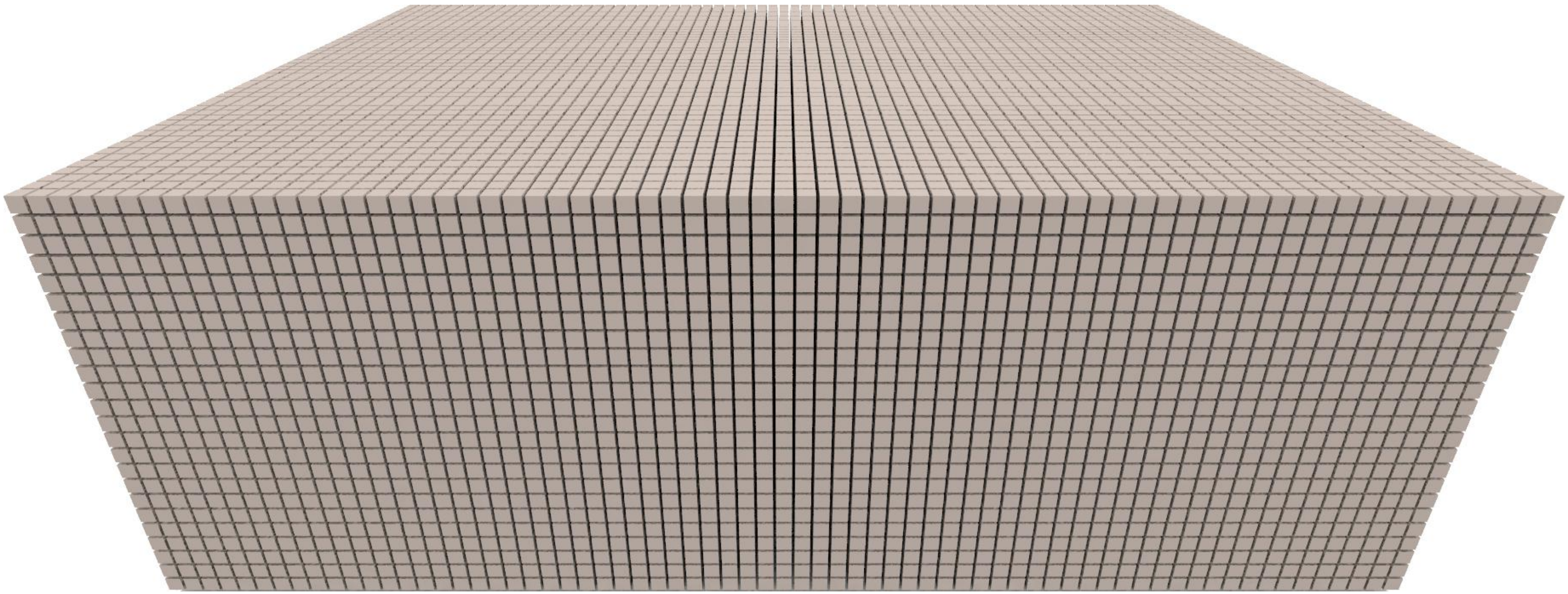
Terrain Deformation Rigid Tire with Lugs

Terrain Deformation – Computations

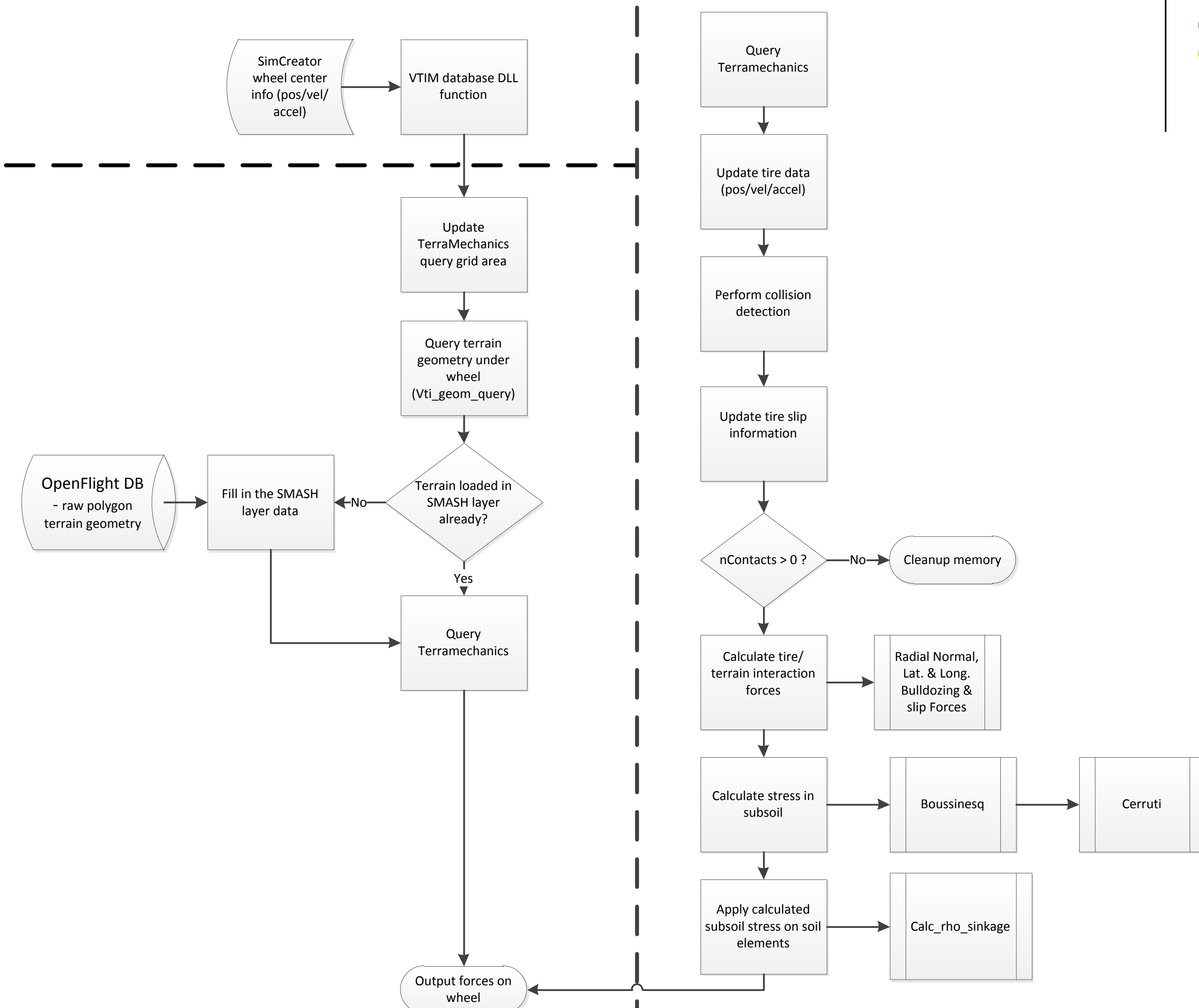
- Each point on the surface now has a volume of soil associated with it
  - Each volume is a vertical soil column, discretized into equally spaced cubes –***subsoil volumes***
- Sum of forces acting on tire are applied to the terrain surface
- Subsoil vertical stress calculated via modified Cerruti & Boussinesq Equations
  - Calculated at ***each*** subsoil volume for ***every*** surface force
  - Sum the vertical stress contributions of all the surface forces at ***each*** subsoil volume
  - Profiling of code showed 99.5% of time is spent computing the subsoil stress
- Vertical stress applied at the top of elements, causes bulk density change resulting in soil deformation for each of the soil volumes according to Ayers & Bozdech
- Overall deformation at the surface is a summation of the contributions of each subsoil volume in the soil column
- Calculation of energy, power to perform deformation is tracked for every subsoil volume
  - Result is a 3-D distribution of bulk density, energy, power

Terrain Deformation

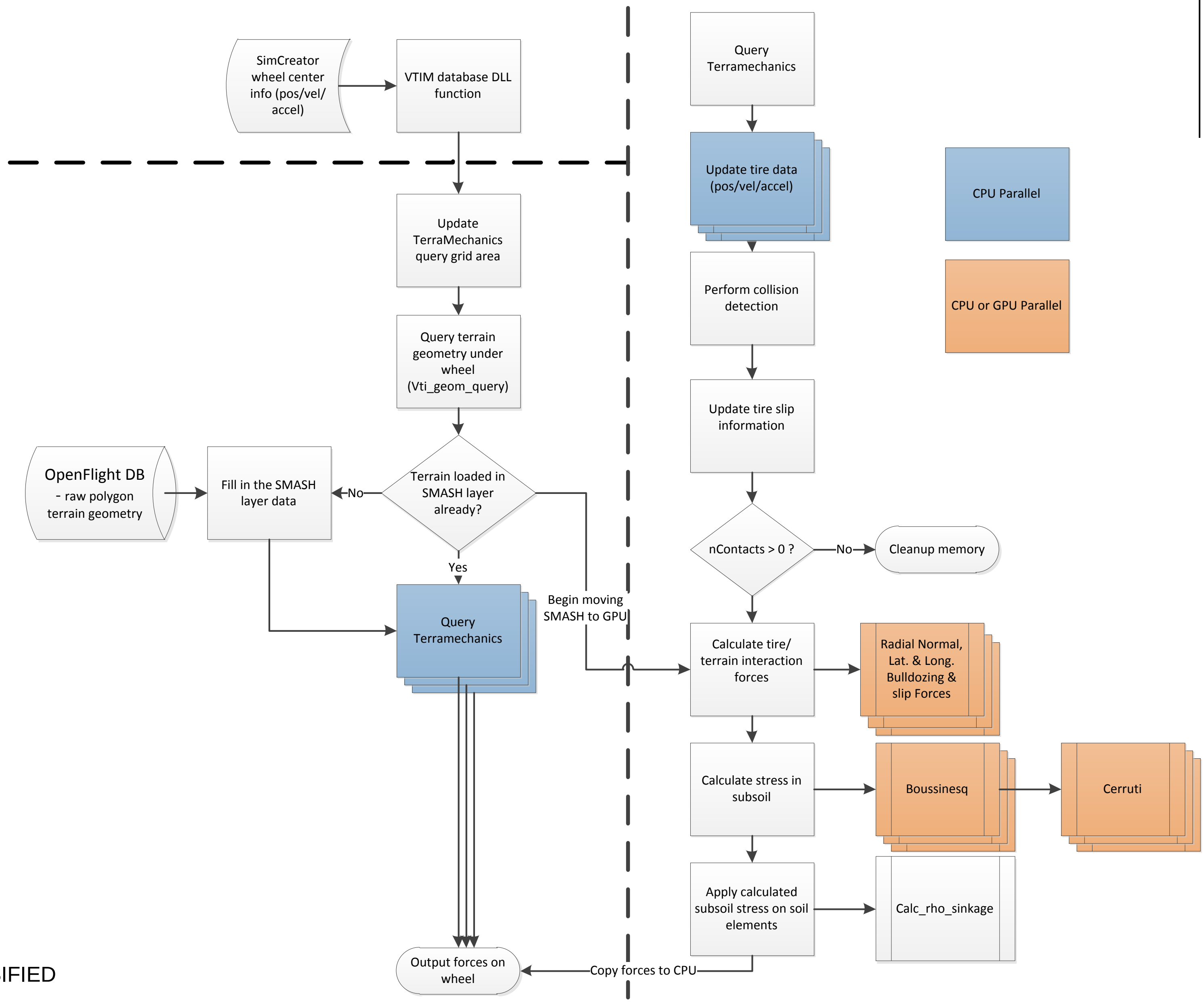
- Discretized volumetric soil layer (flat surface, pre-deformation)



Sequential Implementation



Parallel Implementation



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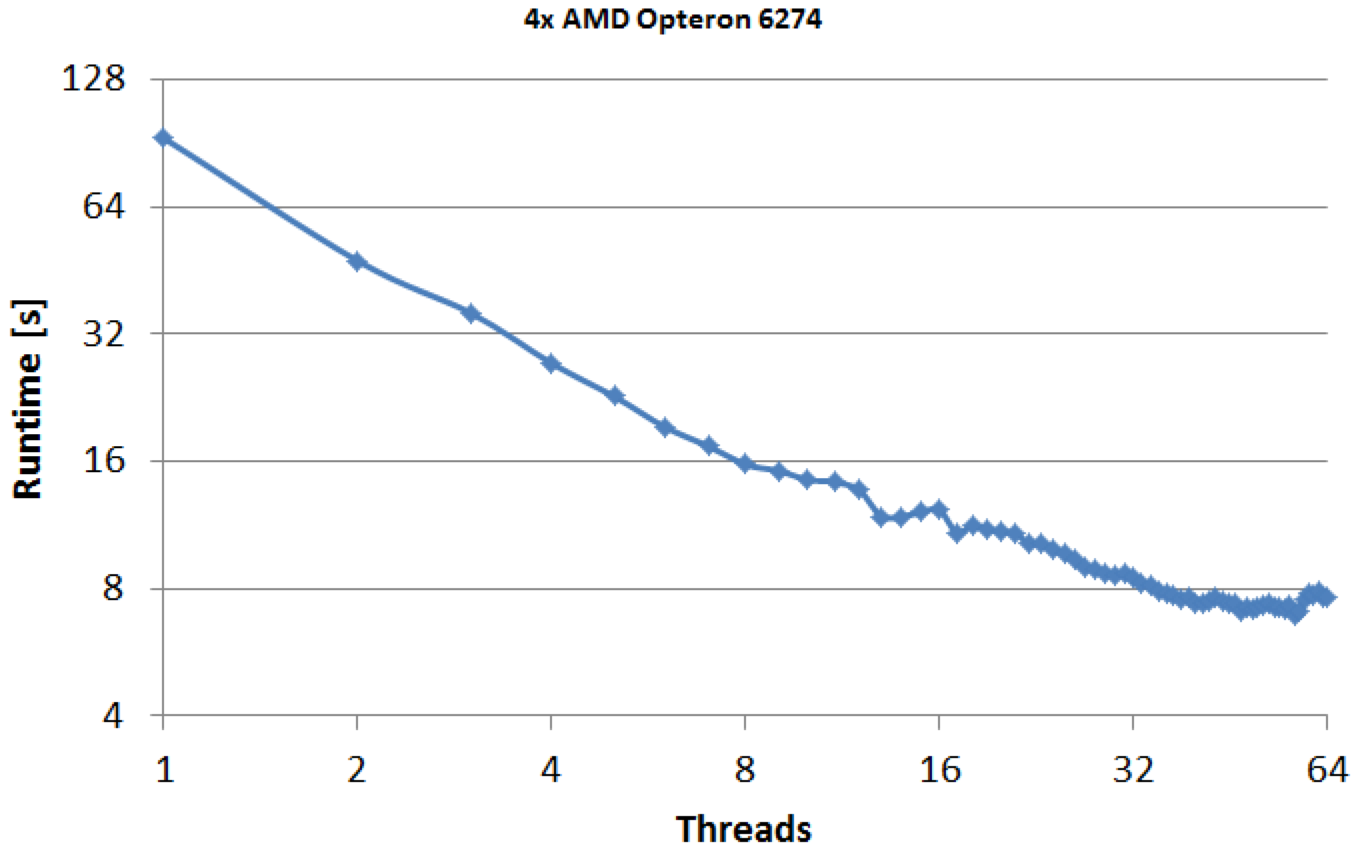
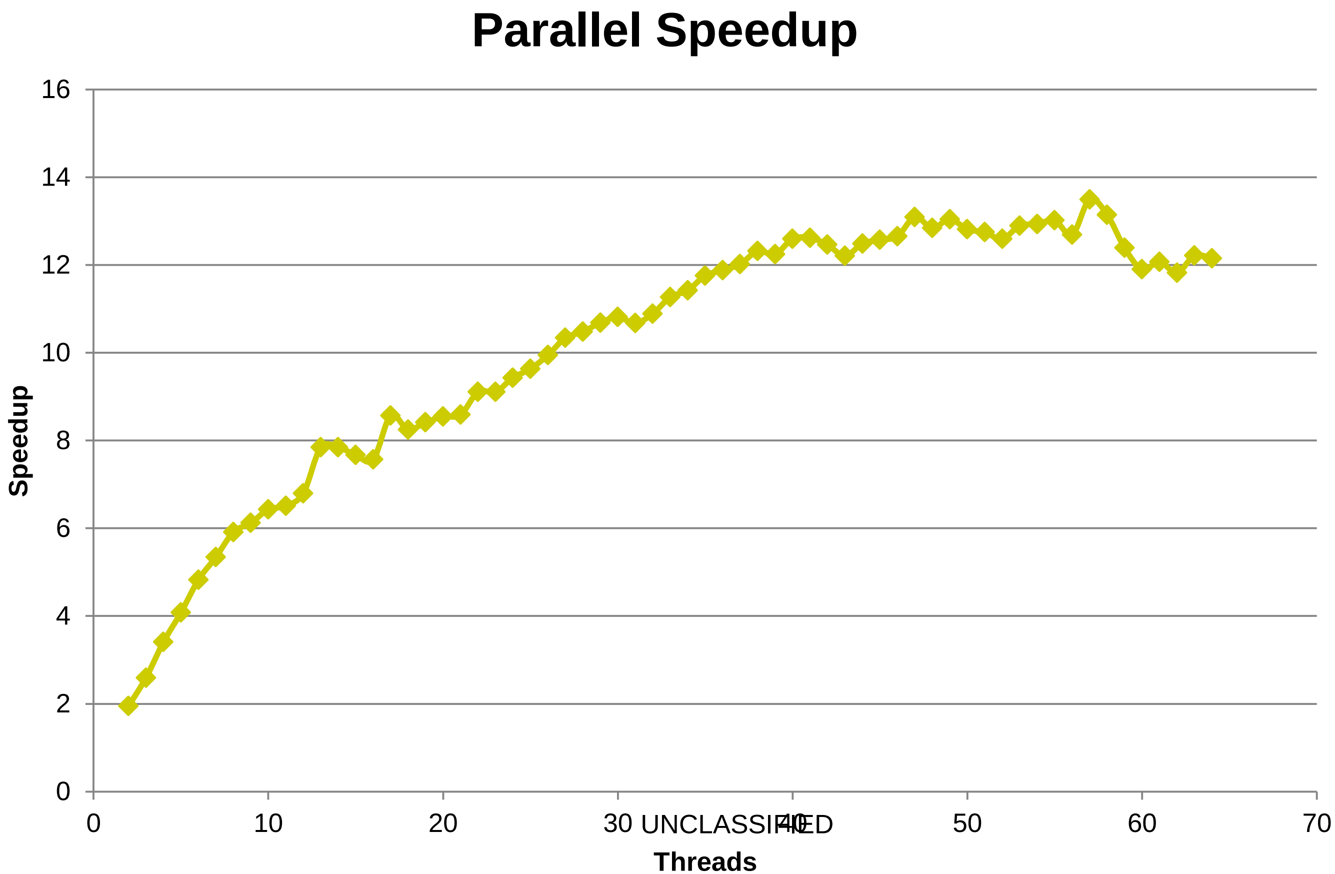
Parallel Scaling

- OpenMP-based
- Computational bottlenecks were targeted
- Parallel code shown to have strong scaling



Parallel Speedup

- Number of threads vs. sequential implementation
- GPU comparison in progress



Conclusions

- VTI terrain database reflects physics-based soil models developed by UT
  - Supports soil non-homogeneities in the vertical direction
  - Visco-elastic-plastic soil mechanics model captures most important soil response effects other than soil flow
- Terrain accepts a set of tire-terrain interaction forces at the interface
  - Allows for tire and terrain models to be developed independently
  - Modularized to use with existing vehicle dynamics software
- Implementation results in parallel computation of soil state change
  - Relies on a stress-bulk density relationship
  - Ability to calculate power, energy required for soil deformation
  - Pursuing both multi-core and GPU avenues

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Thank You.